THE HIGH VOLTAGE CORONA IN AIR.

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Atmospheric air is an extremely good electric insulator. It has low specific inductive capacity, very low conductivity, and a relatively high electric strength, or ability to withstand breakdown or spark-over between high voltage terminals. The name "corona" has been given to the continuous partial breakdown of air subjected to electric strain, and it always appears as a glow or brush discharge confined to one or both high voltage terminals with a region of unbroken air in between.

When voltage is applied to a pair of parallel plates in air and slowly raised, the air withstands the strain up to a definite value of voltage and then breaks down completely with a heavy sparkover or arc between the plates. (See Fig. 1.) In this case the electric field intensity or the number of volts per centimeter is uniform throughout the region between the plates, being equal to the voltage applied divided by the distance between them. The electric intensity at which breakdown occurs in the air at normal atmospheric pressure is about 32 kilovolts per centimeter. If needle points are used, or a hollow cylinder and a wire on its axis, instead of the parallel plates, a quite different behavior of the air appears. On raising the voltage the air breaks down in the form of a brush or glow discharge immediately around the needle points and at the surface of the central wire, but the breakdown is limited to a small distance and there is no sparkover or complete rupture until a much higher value of voltage is reached.

The interest in the cases of the points and the central rod and cylinder lies in the fact that the electric field or voltage gradient is not uniform over the distance between terminals, being highest at the surface of the conductor and more so the smaller its radius of curvature, and also in that the value of electric intensity at which corona first appears may be much higher than 32 kilovolts per centimeter. In fact in these cases values of electric intensity higher than 32 kilovolts per centimeter are reached with no resulting evidence of breakdown or brush discharge.

Evidently we are here in the presence of a striking property of

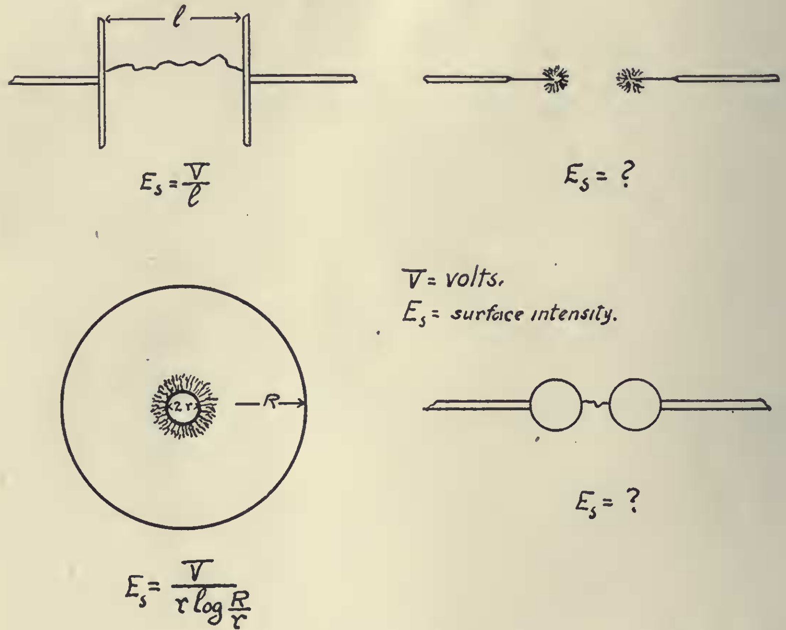

FIG. 1. Spark and Corona.

the air showing a definite influence of the volume of air subjected to electric strain on the intensity at which initial breakdown takes place. It would appear that here is a splendid opportunity for further study of the molecular and atomic structure of the air. The phenomena are extremely definite and constant in the case of the central wire and cylinder, and all of the conditions are susceptible of accurate measurement. However the physicist appears not to be interested in the electric properties of air at pressures in the neighborhood of that of the atmosphere. Professor J. T. Townsend has proposed an interesting explanation of the fundamental law of corona formation in terms of the theory of ionization by collision, but this theory is based entirely on experiments at very low pressures, quite outside the range in which the first definitely marked corona phenomena lie. So far as the writer is aware, Townsend's is the only attempt to coördinate corona phenomena with modern physical theory.

In two particular aspects the corona presents difficulties for the electrcial engineer: first, the presence of corona is always accompanied by a loss or waste of energy; and second, in the presence of corona insulation deteriorates rapidly and the insulating properties of the neighboring air are lowered. In either case the probability of sparkover and shortcircuit is greatly increased.

The energy loss attendant upon corona introduces important limitations in the design of long distance electric transmission lines. The voltage of such lines is made high in order to reduce the magnitude of the current to be carried, and therefore the size of the conductors, the cost of the conductors being a principal item in the total cost of the transmission line. The tendency therefore is to higher and higher values of voltage. As the voltage is increased, however, the corona forming point is reached, and in order to prevent the presence of corona the distance between the transmission wires must be increased.

It is especially important to keep the voltage well below the corona forming value, for above it the loss increases very rapidly. According to F. W. Peek, from measurements made on a section of a modern transmission line, the power loss may be expressed

$$w = kf(e - e_0)^2 \qquad (1)$$

where w is in watts, f is the frequency, e is the maximum value of the voltage and e_0 the voltage at which corona first begins; that is to say, the loss increases with the square of the excess of voltage above the corona forming value. (See Fig. 2.)

The above formula applies to alternating voltage. No complete study has been made of the loss at continuous voltage, probably because little use is made of high continuous voltage in the field of electrical engineering. It has not yet been determined definitely that the law as proposed by Peek is the correct one. The results of R. D. Mershon, one of the earliest observers and workers in this field, on an experimental line at Niagara Falls, are distinctly at variance with the results of Peek, as are those of Jakobsen on an operating transmission line in Peru. On the other hand, the observations of Faccioli in Colorado, and Harding on an experimental

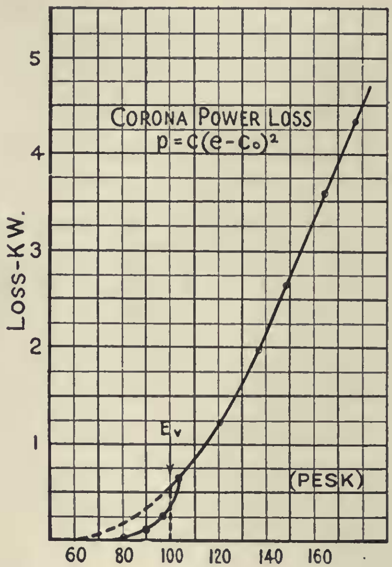

FIG. 2.

line at Purdue University, give results in good agreement with Peek's formula. The difficulty appears to be that the formula does not give correct values for voltages only slightly in excess of the initial corona forming value, the explanation being that surface irregularities and atmospheric deposits of various descriptions on the surface of the wire result in partial corona formation at values below those which would obtain for a perfectly round clean wire. As the voltage is pushed above the corona forming value, these initial losses become relatively small and the rising curve showing the relation between loss and voltage gradually merges into the true curve for a smooth wire. The law as announced by Peek is based on the upper region of this curve. (See Fig. 2.)

No explanation has been offered for the foregoing law, nor does an obvious explanatioin suggest itself. It is not difficult, however, to see that the loss should increase sharply above the critical voltage. Corona first begins when the maximum of the alternating voltage reaches a definite value, which, in the case of a smooth round wire, is very sharply marked. Above this value corona starts on each half wave at this same definite value, whatever the maximum value of the voltage wave may be, and on the descending half wave corona ceases at about the same value or very little below it. Corona is thus periodic and with increasing voltage occupies a larger and larger area at the top of successive half waves of alternating voltage. (See Fig. 3.) In the neighborhood of the critical

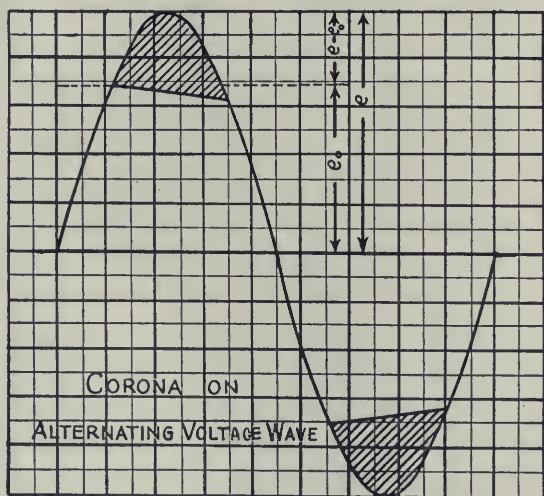

FIG. 3.

corona forming value, when corona is limited to a short interval at the crest of the wave, the loss will evidently be proportional to the frequency since the number of breakdowns per second increase with the frequency. However, with increasing voltage the aggregate time during which the corona actually exists becomes more and more nearly equal for all frequencies. As to the influence of voltage, with increasing voltage the volume of corona increases, and since this means increased ionization and conductivity of the air, the current also increases. The power loss being the product of voltage and the current increasing with the excess of voltage above a certain critical value, we should therefore expect the loss to increase as some power of the voltage higher than the first but that it should be as the second power of the excess voltage in not evident.

Further studies of the nature of the power loss and of the exact law governing it are greatly needed. It seems probable that the observations which have already been made on transmission lines are about as satisfactory as can be obtained in this way. Since it is important to adopt a voltage well below that at which corona forms, and since the values at which corona will start on clean wires are now accurately known, it does not appear likely that transmission engineers will go very far in further investigation. There is here, however, again an admirable opportunity for laboratory study.

It will be seen therefore that it is important to know accurately the laws connecting the physical constants of an electric circuit and the voltage at which corona begins. A number of experimental studies of this question have been made and some of the earlier of these were reported to this society by the present writer several years ago. Since then the law of corona formation has been well established and it is the purpose of this paper to give the results of some of the more accurate measurements. These measurements have been made with the assistance of an instrument in which the otherwise troublesome corona pheonmena have been turned to useful account as a means for the accurate measurement of high alternating voltage. The accurate measurements referred to were made on this instrument, which is called the "corona voltmeter."

The Corona Voltmeter.—The corona voltmeter makes use of the fact that corona forms on a clean round wire in air at a sharply marked definite value of voltage, dependent in a simple relation on the density of the air. The range of the instrument is extended to wide limits by enclosing the wire and cylinder and varying the density of the air.

The essential elements of the instrument are a central rod, or wire, on which corona forms, another concentric cylinder forming the opposite terminal, an outer air-tight containing case in which the air pressure may be varied, and convenient means for determining accurately the first appearance of corona. All of these features are indicated in diagrammatical form in Fig. 4.

In Fig. 4 *A* is the central wire, or rod. *B* is the concentric

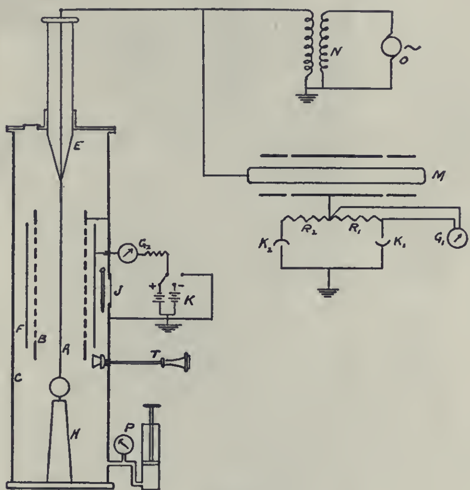

FIG. 4.

cylinder forming the opposite terminal which is connected to ground; *C* is the outer air-tight containing case with air pressure control at the pump *P*; and *E* is a high voltage insulating bushing for connecting the source of high potential *N* to the corona rod *A*; *H* is a porcelain insulator maintaining the lower end of *A* in fixed position.

Two simple methods have been developed for detecting the initial appearance of corona as the voltage on *A* is slowly raised. The first of these makes use of the fact that the presence of corona sets up a copious state of ionization. The cylinder *B* is therefore perforated, and just outside cylinder *B* a continuous surrounding cylinder *F* is placed, carefully insulated from *B*. Connection is made to this outer cylinder through the galvanometer G_2 either directly to ground or with a continuous electromotive force in series. At the first beginnings of corona the air between cylinders *B* and *F* is ionized and therefore becomes conducting, resulting in a sharp deflection of the galvanometer G_2. Fig. 5 is a series of curves showing how sharply the galvanometer deflection occurs as related to corona voltage.

The corona has an audible sound even in the open. When the corona wire is enclosed, as in the corona voltmeter, this sound is gathered and intensified. At atmospheric pressure the ear placed at a small opening in the case C will detect the very first appearance of corona, which will be very sharply marked. In order that the sound may be utilized, when the pressure is of value other than that of the atmosphere, a telephone transmitter is included inside

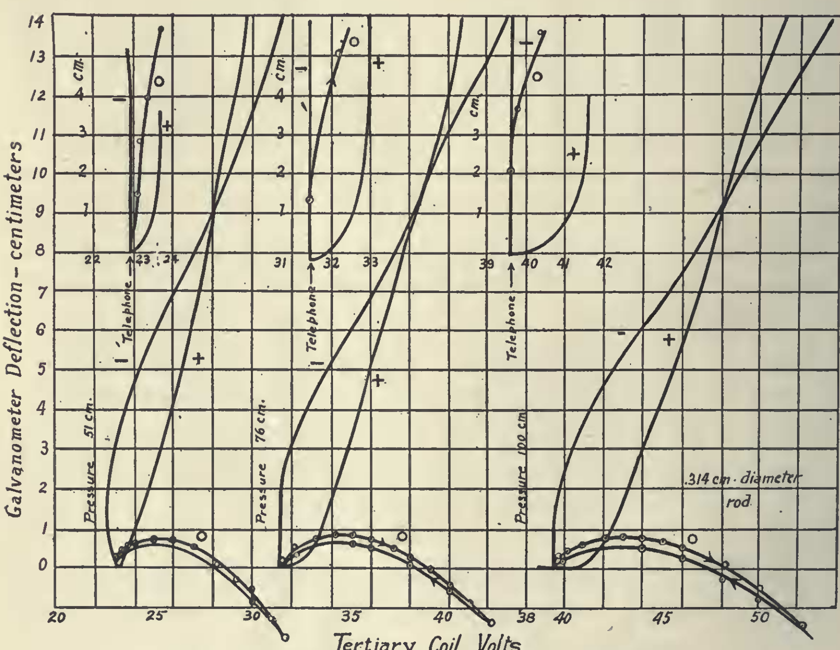

Fig. 5 Galvanometer as Detector of Corona

the casing connected with the receiver outside, as shown at T, Fig. 4. The telephone gives a clear note on the first appearance of corona and the indications of telephone and galvanometer are exactly contemporaneous, as indicated in Fig. 5.

In order to calibrate the instrument and thus determine accurately the law of corona formation, it is necessary to be able to measure accurately the value of voltage applied to its terminals and to determine accurately the first appearance of corona. The instrument, as indicated in Fig. 4, is in fact the result of a long series of experimental studies of corona formation and the gradual development of methods of controlling and determining all the factors which enter. It has been known from the beginning of these studies that corona forming voltage gradient depends on the diameter of the wire and on the density of the air, no other factors entering. Moisture content of the air, for example, has no influence on corona forming intensity. A possible exception is the frequency of the alternating voltage which appears to have a very small influence, too small, however, to be of importance within the commercial range of frequency. The instrument therefore provides means for observing the pressure and temperature at P and J, and also means not indicated in Fig. 4 for removing the central rod A so that another of different diameter may be substituted.

The method of measuring the applied voltage is also indicated in Fig. 4. It consists of connecting an air condenser M, of known capacity, in parallel with the conora voltmeter and of measuring the charging current of this capacity. This charging current is a direct measure of the maximum value of the alternating voltage in terms of the capacity of the condenser and the frequency of the generator O.

The alternating charging current is connected to earth by the divided circuit R_1K_1 and R_2K_2. R_1 and R_2 are noninductive resistances and K_1 and K_2 are rectifying Fleming valves passing the positive and negative half waves respectively. R_1 therefore carries a pulsating unidirectional current, the average value of which may be measured on the calibrated d'Arsonval galvanometer G_1. The impedence of the $R_1K_1 — R_2K_2$ circuit is negligible compared with that of the condenser M. In order to withstand the high voltages used, and that it might have no loss, an air condenser was used at M. The condenser was of cylindrical type with flaring guardrings, as shown in the photograph, Fig. 6. The cylinders were made from cast iron water pipes, the diameters of the inner and outer members being 29.5 cms. and 49.3 cms., respectively, and the length of the central section of the outside member 76.2 cm. The capacity of the condenser as measured was 8.28×10^{-15} microfarads.

In making observations the voltage of the generator O was slowly raised and at the instant corona appeared, as indicated by the galvanometer G_2 and telephone T, the galvanometer G_1 reading the

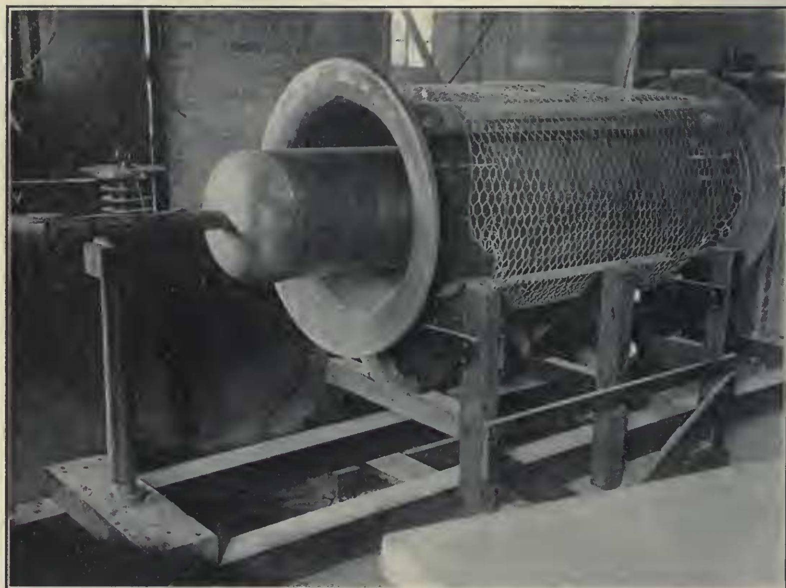

FIG. 6. Air Condenser.

condenser charging current was read, and at the same time the temperature and pressure at J and P. The frequency was also accurately measured by comparison with a standard tuning fork. The reading of the calibrated galvanometer G_1 gives the charging current of the air condenser M which, with the frequency, leads to the maximum value of the alternating electromotive force corresponding to corona formation. It only remains therefore to connect this critical value of voltage with the conditions as to temperature and pressure to arrive at the law of corona formation.

The form of the relation between voltage, temperature and pressure and the diameter of the corona forming wire, as agreed upon by several observers in recent years, is usually stated in the form

$$E = A\delta\left(1 + \frac{B}{\sqrt{\delta r}}\right), \tag{2}$$

in which E is the critical or corona forming voltage gradent at the surface of the wire expressed in kilovolts per centimeter, r is the radius of the wire in centimeters, and δ the relative density of the air, having the value

$$\delta = \frac{3.92p}{263 + t}, \tag{3}$$

p being the pressure is centimeters of mercury, and t the temperature in degrees Centigrade.

A more convenient form of the relation for our purpose is

$$\frac{E}{\delta} = A + \frac{B'}{\sqrt{\delta r}}, \tag{4}$$

which gives a linear relation of $E\delta$ and $1/\sqrt{\delta r}$.

The above relatively simple relations have now been corroborated by a number of observers with fairly close agreement as to the value of A and B. The form of the law is the same for both continuous voltages and crest values of alternating voltages. With continuous voltage, however, there are appreciable differences in the values of the constants A and B as between positive and negative corona forming wire, the form of the law in each case remaining the same.

No attempt will be made in this place to give a complete review of the large number of observations which have been taken on ten different sizes of corona forming rod under wide variations of relative density δ. Table 1, however, gives several sets of readings and indicates, particularly in columns 7 and 8, the accuracy with which the observations repeat themselves. Column 9 gives the readings of galvanometer G_1 measuring the condenser charging current, and column 14 is the reading of an ordinary alternating voltmeter connected to the low voltage terminals of the high voltage transformer. The readings of this voltmeter were not used in the calculations, but its indications provided at all times a convenient means for determining the constancy of circuit and other experimental conditions. The observations were all collected in groups corresponding

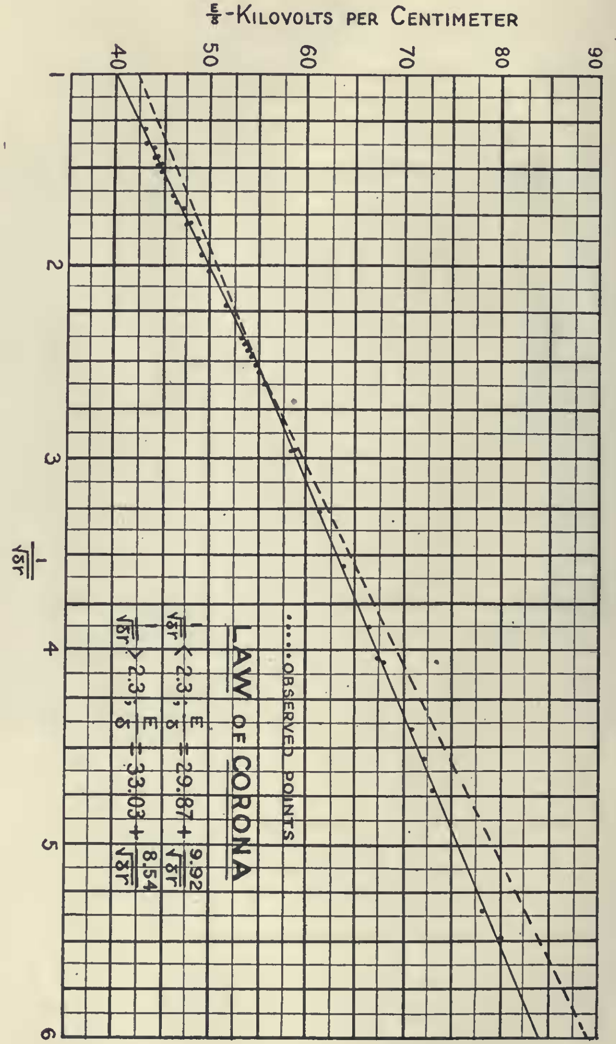

Fig. 7.

to approximately the same values of δ for each particular size of corona rod, and the values of E/δ and $1/\sqrt{\delta r}$ were calculated in each case. Obviously E, the value of the surface electric intensity on the corona forming rod, is obtained from the measured value of the voltage and the dimensions of corona rod and outer cylinder *B* (Fig. 4). As these results were obtained they were plotted, and Fig. 7 shows the resulting relative location of the points. The equations of the straight lines were obtained by a method of analysis proposed by Steinmetz for deriving from a series of experimental values the most probable equation.

It will be seen that there is a linear relation between E/δ and $1/\sqrt{\delta r}$, but that there are two such relations resulting in two

TABLE 1.

CORONA VOLTAGE READING.

.4765 Cm. Diam, Rod.

Freq.	Bar Press.	Temp.	Press Left.	Gauge Right.	Corr. Abs. Press.	Galvanometer. Corona Reading. Left.	Right.	Mean.	Calibration. Left.	Right.	Volts 499 Ohms.	Milamp per Div.	Terr. Coil Vol.
60.03	75.56	18.9	72.30	8.60		10.22	10.30	10.26	10.26	10.29	.3890		65.9
						10.23	10.30	10.26					65.95
					139.74							.07590	
						10.22	10.30	10.26					65.95
		19	72.00	8.90		10.22	10.30	10.26	10.23	10.30	.3891		65.95
60.04	76.12	19.8				6.22	6.23	6.22	6.19	6.21	.2348		40.2
						6.19	6.23	0.21					40.1
					76.12							.07591	
						6.19	6.22	6.20					40.1
		20				9.19	6.22	6.20	6.18	6.22	.2348		40.05
60.03	76.50	18.8	19.97	60.48		3.46	3.48	3.47	3.42	3.44	.1308		22.5
						3.47	3.49	3.48					22.5
					36.25							.07642	
						3.48	3.49	3.48					22.3
		18.7	20.07	60.33		3.48	3.50	3.49	3.42	3.44	.1308		22.4

straight lines of different slopes, these lines intersecting at the value

$$\frac{1}{\sqrt{\delta r}} = 2.3. \tag{5}$$

In other words the law of corona must be expressed by two equations, one for values of $1/\sqrt{\delta r}$ below 2.3, this equation being

$$\frac{E}{\delta} = 29.84 + \frac{9.93}{\sqrt{\delta r}} \tag{6}$$

and the other for values of $1/\sqrt{\delta r}$ above 2.26, the equation in this case being

$$E = 32.96 + \frac{8.56}{\sqrt{\delta r}}. \qquad (7)$$

The sharp change in the slope of the linear relation between E/δ and $1/\sqrt{\delta r}$ finds its explanation in the fact noted above as to the difference of behavior as regards corona formation between positive and negative corona forming wires, or rods. As has already been stated, the form of the law is the same for both positive and negative rods, but the constants of formula (2) are different. This is equivalent to saying that for values of $1/\sqrt{\delta r}$ below 2.26 negative corona appears first and the law is as given by formula (6). For values of $1/\sqrt{\delta r}$ above 2.26 positive corona appears first and the law is as given by formula (7).

All of the measurements leading to these results were made in terms of laboratory standards and by use of the best available equipment and experimental methods. No account is given here of the various experimental difficulties, precautions and calibrations, a complete account of these being given in a forthcoming paper in the *Journal of the American Institute of Electrical Engineers*, May, 1920. The conditions of accuracy are discussed there and show that the foregoing formulæ are probably accurate within an experimental error of considerably better than ½ per cent.

Considered as an instrument for measurement of voltage, it will be noted from Table 1 how definitely the readings repeat themselves. The law of corona, having been determined by the accurate methods outlined above, the corona voltmeter may therefore be used itself as an instrument for the direct measurement of voltage, in fact its calibration is inherent in its dimensions and it becomes a natural secondary standard.

Fig. 8 shows the exterior of a corona voltmeter suitable for measurements of voltage up to 200,000 volts. The accurate measurements referred to above were made with this instrument. It is 9 ft. 10 in. high, of which 3 ft. is in the insulating terminal. The outside diameter is 1 ft. 10 in. An instrument suitable for voltages up to 300,000 volts and above is now under construction and will shortly be put into operation by a well-known hydro-electric power company.

In operation the corona voltmeter may be used in two ways. *First,* it may be set for any desired value of voltage by adjustment of pressure in the instrument. In order to do this the temperature

FIG. 8. Corona Voltmeter for 200,000 volts.

of the air in the instrument is read and the value of the pressure for any desired value of voltage may then be computed from formulæ 3, 6 and 7. Ordinarily this will be done through reference either to a curve or a table prepared from the formula. The pressure having been set at the proper value the voltage is then slowly raised until corona appears. This is the more common method, as the instrument is chiefly of value in the testing of high voltage apparatus, such as transformers and insulators, in which case it is desirable to apply a definite test voltage as determined by the rating of the apparatus in question.

Second, the corona voltmeter may also be used for measuring an unknown voltage by adjusting the pressure for a value of voltage known to be higher than that to be measured and then gradually lowering the pressure until corona appears.

The instrument as illustrated in Fig. 8 provides a ready means for removing the corona rod either for cleaning or for the substitution of one of a different diameter. A clean rod may be used for many hundred observations without deterioration of its surface.

The corona voltmeter offers many important advantages over existing methods of measuring high voltage. The only other method of direct measurement available is that of the sphere gap or spark between metal spheres. This method is subject to serious error due to the proximity of surrounding objects, and has a different calibration curve for the cases of one sphere grounded and both spheres insulated. It also has the serious disadvantage that it necessitates a spark discharge across the circuit and that the high voltage terminals must be manipulated for each new adjustment. The casing of the corona voltmeter is grounded at all times, and provides a complete electrostatic screening making the instrument free from all types of outside disturbance. It causes no discharge and draws no current from the high voltage terminals. Changes of setting to meet new values of voltage are accomplished merely by changing the air pressure in the instrument. A number of lesser advantages need not be enumerated here.

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